Development of an Air-Humidity and Pressure Control System for Multi-Cavity Building Envelopes, Membrane Cushions, and Façade Systems: Proof of Concept

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Abstract

Multilayer air-supported membrane structures are operated mostly uncontrolled by maintaining a set pressure and the lowest possible supply-air humidity. This leads to high energy use from constantly maintaining the default pressure and the continuous drying of the supply air necessary to avoid the cushions collapsing and condensation inside the air chambers.

Controlling pressure and humidity interactively across all chambers of the membrane cushion will enable ETFE foil manufacturers to apply functional coatings to foils, use thin-film PV, etc., which has been challenging due to the high sensitivity of coatings and applied materials to mechanical (stretching) as well as chemical (oxidation) impacts.

To address those challenges, the presented work studied the air conditions and flow patterns within the air chambers of multilayer ETFE systems. A mock-up of a 5-Layer (4-Chamber) ETFE membrane cushion was specially designed and constructed for testing. Hardware and software solutions were developed to introduce a pressure and dew-point-based humidity controller. The study also considered options for separate pressure control of the chambers and thereby controlling the stress on ETFE foils. Parametric studies were carried out to estimate the reduction in electrical energy consumption during operation. First observations showed the prevention of condensation inside the chambers and a reduction of foil stretching.

Key results will also be useful for other building envelope applications that share some key requirements, such as closed-cavity façades, for example. As of now, feasibility is demonstrated.

Keywords

Membrane cushions, functional ETFE foils coating, multilayer membrane structure, control of air quality, low energy air supply, and control systems

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1 INTRODUCTION

Ethylene Tetrafluoroethylene (ETFE) is a clear fluorine-based co-polymer (Architen Landrell, n.d.; Knippers et al., 2011). It is one of the newest of the polymer family; only 100 years old–a great contrast to many of the other materials commonly used in the building industry (Knippers et al., 2011). When extruded into a thin film (often called foil), it forms a single-layer membrane. Foil thickness is usually between 100 and 300 µm. The stronger, more durable and UV-permeable extruded ETFE foil did not become available until the mid-1970s (Architen Landrell, n.d.; Knippers et al., 2011). It was initially used to replace the glass in glasshouses and was not employed for building envelopes until after its use on a glasshouse in Arnheim in 1982, which paved the way for its use in architecture (Knippers et al., 2011). There are basically two ways of permanently installing ETFE foils in buildings: firstly, by mechanical prestressing (anticlassical surface curvatures) and secondly by utilising the load-bearing effect of air (synclastic surface curvatures). The latter can be implemented in so-called air domes, where the interior has a slight overpressure relative to the exterior (rare application), or in so-called membrane cushions. Here, multilayer ETFE foils are clamped and/or welded together at the edges and supported by an aluminium perimeter extrusion (Knippers et al., 2011). When filled with air, one or more air chambers form, depending on the number of layers. The latter, along with the inclination, determines the thermal insulation (U-Value) of the cushion as a construction element. The inner layers of the cushion can be much thinner than the outer ones because they are subjected to a lower prestress and make only a minimum contribution to carrying the loads (Knippers et al., 2011). Since the 1950s, membrane cushions in general (also using coated textile materials) have been considered attractive construction elements. ETFE foils, in particular, offer tremendous savings, since they are only 1% the weight of glass and transmit up to 95% light (Architen Landrell, n.d.; Knippers et al., 2011).

FIG. 1 ETFE cushions; Allianz Arena, Munich, Germany (source: author)

1.1 GEOMETRY AND CONSTRUCTION OF MEMBRANE-CUSHIONS

The main span of a cushion made from a typical material (e.g. ETFE foil) is limited to a few metres. To overcome this limitation, groups of cushions are added to a primary structure to form a building envelope (Fig. 1). The geometry of each cushion depends on the layout of the primary structure framing the cushions (Fig. 2 and Fig. 3) (Knippers et al., 2011).

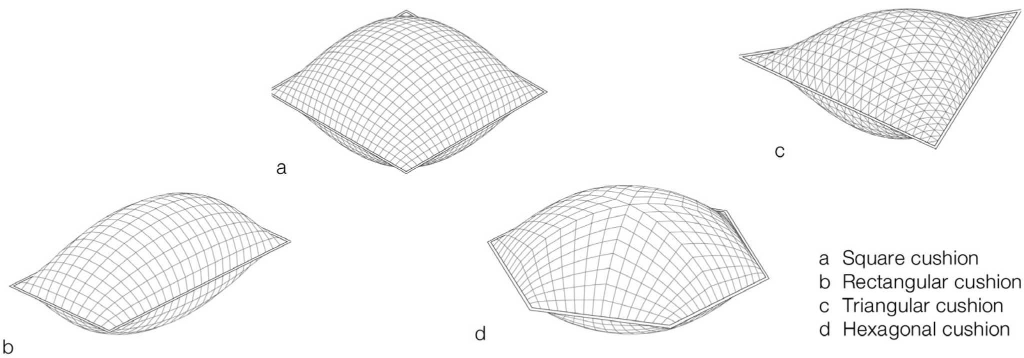


FIG. 2 Different shapes of pneumatically prestressed surfaces (Knippers et al., 2011, p. 142)

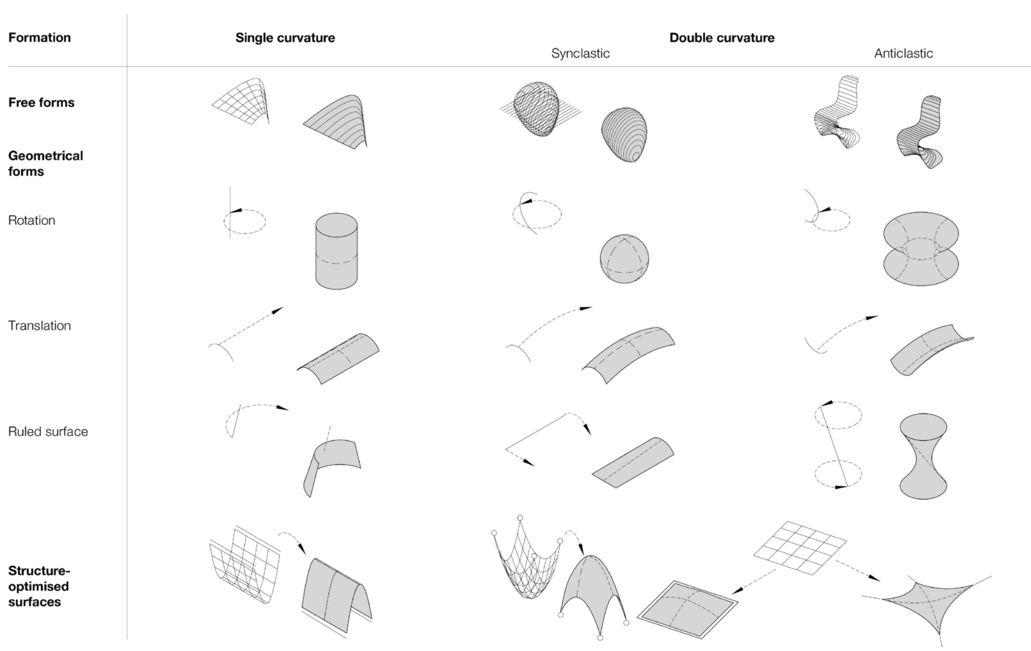


FIG. 3 The principles for forming curved surfaces (Knippers et al., 2011, p. 137)

1.2 MEMBRANE CUSHIONS AS PNEUMATIC STRUCTURES

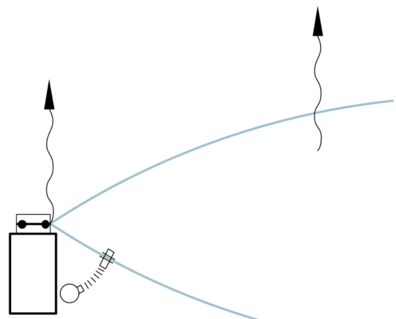
The principle of pneumatic forms of construction is described in detail in Knippers et al. (2011, p. 192). According to this source:

It is based on creating a pressure difference between two spatial areas. Pneumatic structures include air-supported structures (the entire usable interior space is at a pressure higher than that of the outside air) as well as air-inflated structures (certain parts are stabilised by an overpressure using air-filled cushions or tubes). An air supply must be provided for both types so that they remain usable and stable. The pressure in a pneumatic structure must be maintained at a constant level. However, pneumatic structures built from conventional foil and membrane materials can never be constructed completely airtight. Leaks are unavoidable in the following areas:

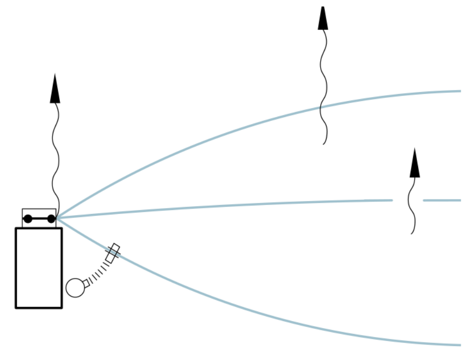
- via the material itself (low effect)
- via faults in the material
- via the joints in the material (welded or glued seams)
- via the air supply connections
- possibly via the clamping and edge details

The internal pressure must be regulated continually to compensate the constant losses and to cope with the pressure fluctuations of the outside air, wind loads and potentially snow loads. Depending on the size of the structure, one inflation unit could be responsible for all the cushions, or several units may be required, each of which is connected to a particular group of cushions. The installation can be designed in such a way that it is able to increase its output considerably to cope with high snow loads by raising the internal pressure in all or certain cushions.

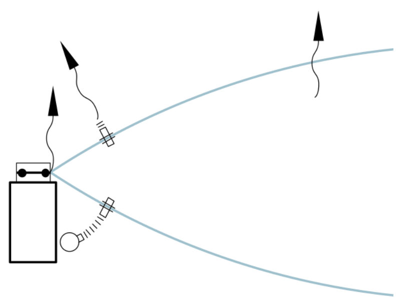
The air inlet to each cushion is generally close to the edge clamp because this is where the supply hoses can be easily routed and fixed (Fig. 4). The connection itself must be flexible in order to cope with the inflation procedure and the unavoidable movements of the cushions in use; ETFE hoses or other elastic polymer hoses are the best choice. The main lines and the secondary duct system are typically made from spiral-wound pipes. If these remain exposed and the aesthetics are important, pipes made from polymers or other materials (e.g. stainless steel) can be used. Very small hose diameters of 10-20 mm would be adequate for normal operations, for maintaining the air pressure at the necessary level. However, it is very difficult for systems with small hoses to cope with the drop in pressure if a cushion is damaged. Therefore, air hose diameters of 40 mm and more have become established in practice. Occasionally, additional outlet safety valves are fitted and normally equipped with silencers to suppress any disturbing whistling noises (Fig. 4c). It may be necessary to fit such valves when a certain pressure level must be maintained very accurately or the inevitable leaks in the structure are not adequate for the necessary flushing of the cushion with the fresh air. The air inlet to each cushion should include a safety/check valve to maintain the pressure for up to 8 hours even if the fans are not functioning. (Knippers et al., 2011, p. 192)



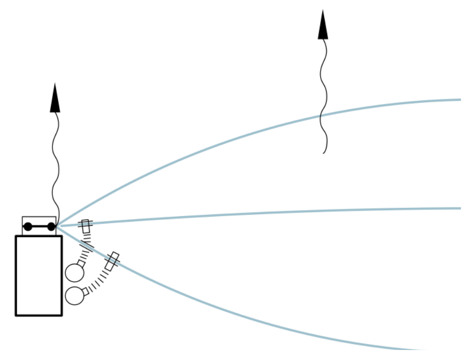
a *Single air inlet; air escapes via leaks in the surface and at edges*



b *Cushion with two chambers and single air inlet; leakage air opening in central layer*



c *Air supply with control valve; the air escapes via leaks in the surface and at edges, and also via a silenced outlet valve (air pressure in cushion regulated)*



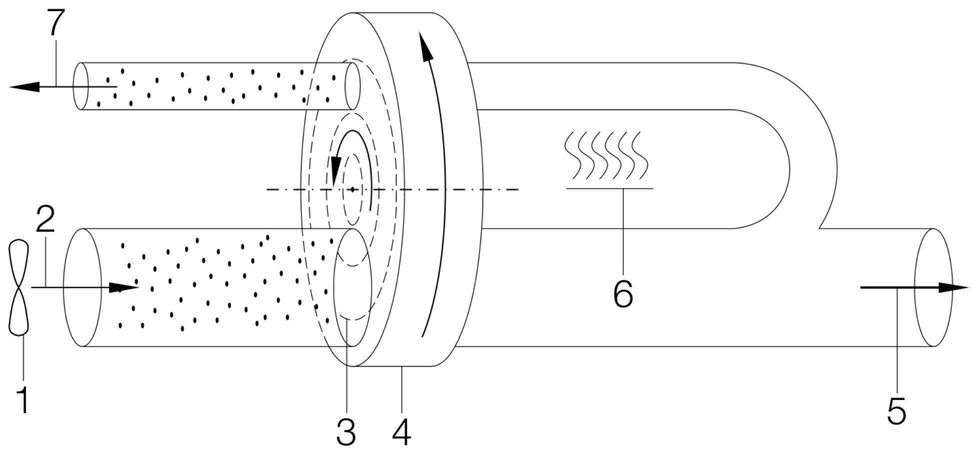
d *Cushion with two chambers, each with its own air supply (various pressure levels possible)*

FIG. 4 Options for connecting the air supply to cushions (Knippers et al., 2011, p. 192)

1.3 AIR-SUPPLY SYSTEMS

The following is also mentioned in Knippers et al. (2011, p. 193):

The air supply is provided not only for maintaining the pressure in the cushions, but also for ensuring that the air within the cushions is sufficiently dry. This prevents condensation and algae growth inside the cushions. Pneumatic structures should therefore be supplied with pretreated air and so the treatment plant normally consists of filter, fan/compressor and a condenser drier or a dehumidification unit with a heating battery (absorption dehumidifier; Fig. 5). Dehumidifying the air accounts for a considerable proportion of the energy consumed by the air-supply system; there is room for developing alternative concepts here that require only a minimum amount of primary energy. Filtering the air is important because otherwise dust and dirt could enter the cushions, from where it is impossible to remove. All the components of the treatment plant should therefore be accessible for regular maintenance and repairs. The system should be flushed through with dry air to remove any dust, dirt, foreign matter or pollutants prior to connecting the hoses to the cushions for the first time.



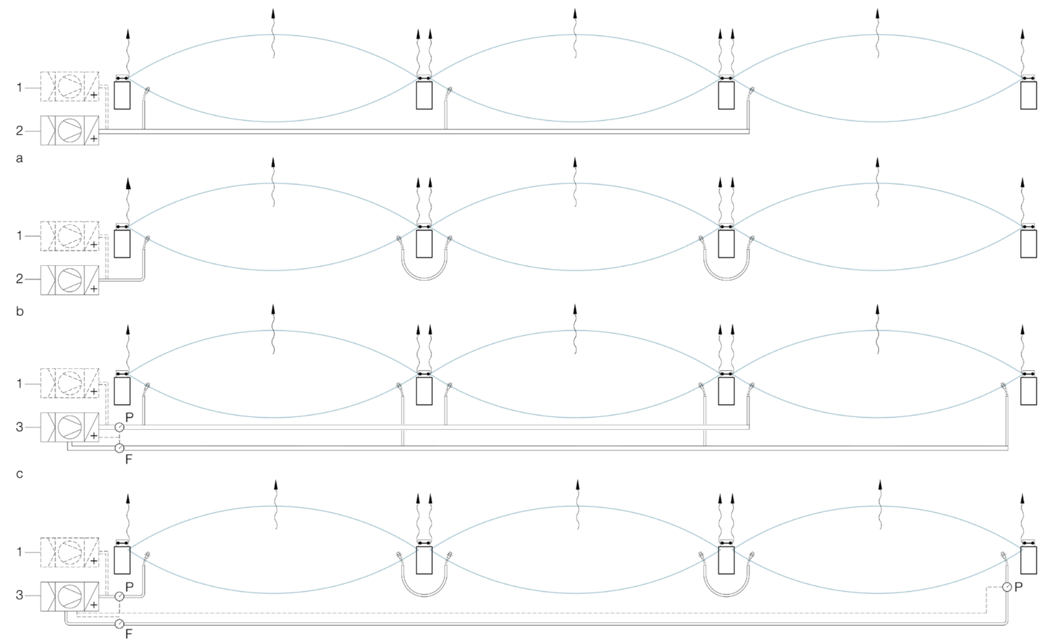
1 *Fan*
2 *Moist supply air*
3 *Moisture absorption*
4 *Silica gel rotor*
5 *Dehumidified air*
6 *Heating battery*
7 *Moist exhaust air*

FIG. 5 Inflation unit with absorption dehumidifier (Knippers et al., 2011, p. 194)

It is usual to connect several cushions together to form a group which is then supplied by common air-supply systems in a series or parallel arrangement. A parallel system (Fig. 6 a). achieves a very constant pressure level in the individual cushions with just one connection. Furthermore, individual cushions are easily replaced because they can be readily disconnected from the system without interrupting the supply to the other cushions. An additional common supply pipe is required, the size of which normally has a much greater diameter (approx. 100 – 150 mm) than the branches (approx. 40 – 50 mm). In a series installation, all the cushions (apart from the last one in each series) requires two connections (Fig. 6 b). The pressure level generally drops gradually from the first to the last cushion. Both systems are regulated by the pressure, sometimes combined with humidity control, and both suffer from losses. This type of system generally includes absorption dehumidifier.

Quick detection of major breakdowns and leaks is achieved with a timer control, i.e. an unusually long operating time triggers an alarm. Such detection systems are becoming increasingly important for safety reasons.

Return air systems, the characteristic feature of which is the return flow line, are being used more and more in order to save energy in air supply installations (Fig. 6 c and d). This mainly reduces the energy required for dehumidifying the air because this unit only functions when activated by signals from sensors. Measuring the relative humidity in the cushion, which is usually carried out at the centre of the circuit, enables the system to respond to the changing weather conditions. Series and parallel systems are possible with return air installations as well, with the same advantages and disadvantages as for those systems with inherent losses. Two pressure sensors are generally recommended for a series installation, which measure the values at the start and end of the chain and, for example, calculate a mean value for the control. (Knippers et al., 2011, p. 193)



1 *Backup supply*

2 *Primary air supply (Filter + Inflation unit + Dehumidifier)*

3 *Return air system with sensors (P: sensor for air pressure – F: sensor for humidity)*

FIG. 6 Air supply systems with: parallel (a), series (b), return air + parallel (c), return air + series (d) connections (Knippers et al., 2011, p. 193)

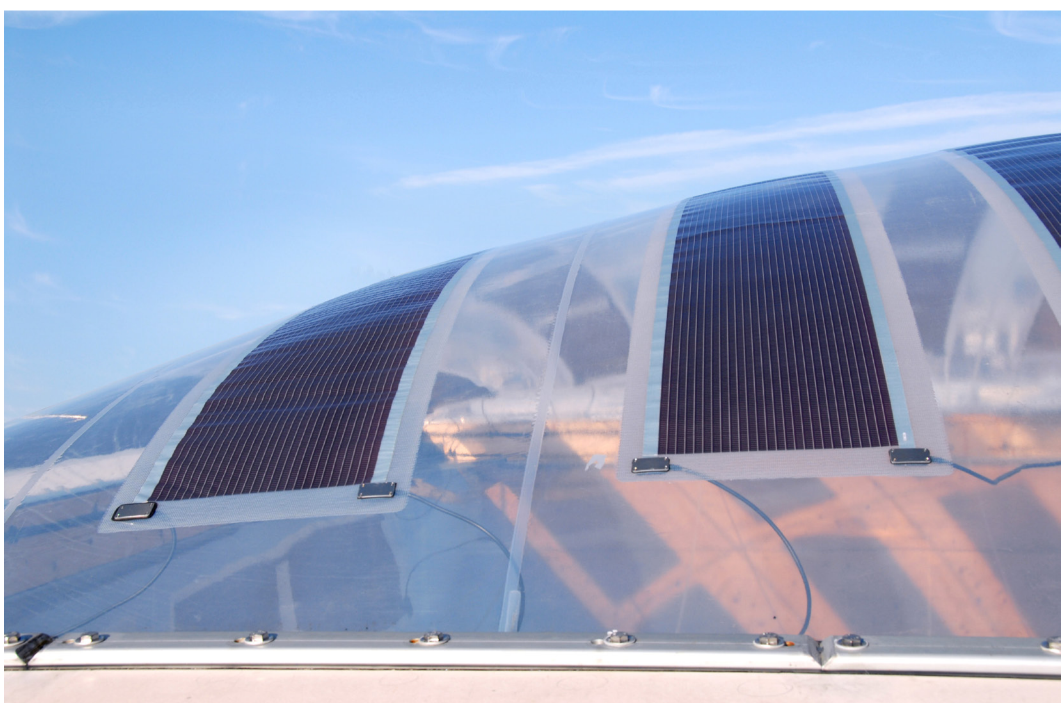
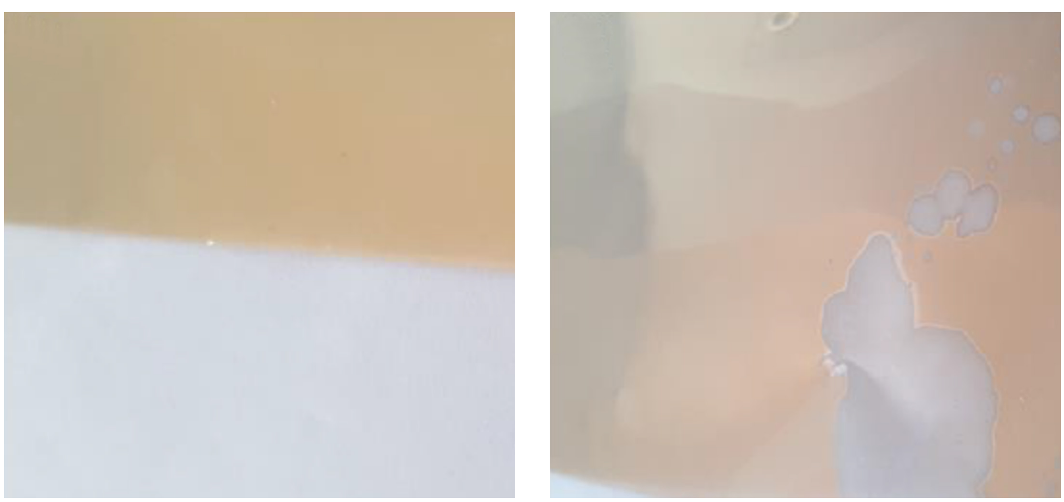


FIG. 7 PV laminated to structural ETFE top layer of a cushion (source: author)

1.4 STATE OF THE ART

Membrane cushions are kept inflated on site, ideally via a blower that continuously supplies air to all of the chambers at a preset pressure. Preset pressures range from the typical 350 Pascal up to 700-1000 Pascal, e.g., for snow pressure. Furthermore, the air supply must be continuously dried (via an electric dryer) to prevent mould formation caused by condensate inside the cushions and at all joints or connection points (Knippers et al., 2011). In practice, this airflow is an open loop, i.e., it is not normally circulated, and any leakage from the cushion escapes to the environment. This behaviour requires a more or less continuous operation of both the blower and the dryer resulting in high energy consumption.

On the other hand, the functionality of membrane cushions can be improved by applying functional coating layers (films) to ETFE foils, which provide low emissivity or selective solar shading properties. Those reflective coatings, or even integral photovoltaics (Fig. 7), are examples of added and improved functionality used in membrane cushions (Knippers et al., 2011). A couple of recent research projects were dedicated to investigating and testing the performance of such functional coatings and laminates applied to ETFE membrane cushions under typical working conditions (J. Cremers et al., 2020; Jan Cremers et al., 2019; Hinze et al., 2020; Manara et al., 2018; Siefert et al., 2019). Despite the promising results at first glance, structural failure of the functional coating layer was noticed after some months of operation. The uncontrolled air conditions inside the membrane cushions result in pressure and temperature fluctuations within each air chamber. Hence, those functional coating layers are subject to numerous volume changes, and corrosion is caused by condensation and insufficient air purity. This eventually leads to damage and degradation of the coating layer (Fig. 8). Developing a method to continuously monitor and actively control the air conditions and quality inside membrane cushions would greatly advance this promising coating technology.



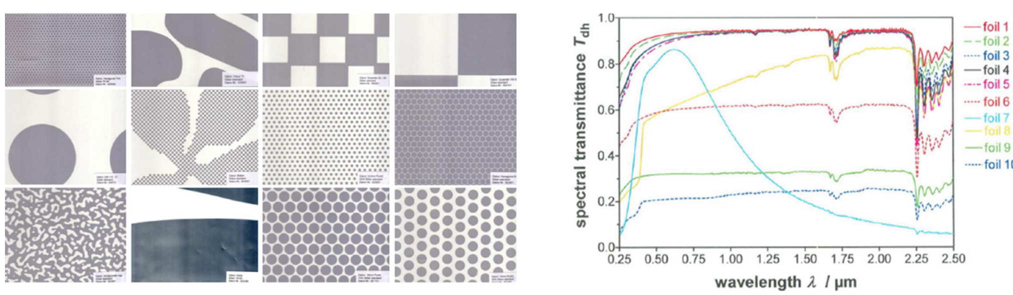
a *b*

FIG. 8 a) Selective, metallised ETFE film against white background – b) Degraded coating after severe environmental stress: temperature, strain, condensate (source: author)

1.5 RESEARCH FRAMEWORK

This paper presents a cooperative research work between academia and industry. The goal was to develop a fully automated control method for a scalable roof or façade structure made of 5-layer ETFE membrane cushions. The developed process focuses on monitoring and controlling pressure, temperature, and humidity in all air chambers around the clock to lower the energy demand of the air supply system and to improve cushion service and maintenance. Among the project's targets was also to test and further develop a novel air flow valve control system, designed by the industry partner, to allow the flush of the air contained in the cushions (only when required) with dry air in a closed loop. An automatic control, as such, leads to an efficient operation of the membrane cushion system.

On the one hand, the energy consumption of the air supply and of the air dryer would be significantly reduced thanks to the new demand-driven mode of operation, rather than continuous operation. On the other hand, the improved air quality inside the air chambers and the more stable volume of the air, through the active control of temperature, pressure and humidity, should enable not only a reliable long-term operation of common functional coating layers, but should also be an enabler for new coating concepts for ETFE foils with application-specific membrane technologies. This includes, for example, film coatings that limit light transmission while maintaining foil transparency. Moreover, coatings that enable wavelength-dependent transmittances are also possible (Fig. 9), thus enabling the ETFE membrane cushions to be directly integrated into the active control of air conditioning in buildings.



a *b*

FIG. 9 a) Printed ETFE foils – b) Wavelength-dependent transmission through differently printed ETFE foils (Manara et al., 2018)

2 METHODOLOGY

The innovative core of this project is the development of a novel method to control pressure, temperature, and humidity in all air chambers of a 5-layer ETFE membrane cushion roof and façade structure (Fig. 10). To achieve this ultimate goal, multiple work packages were defined in the project. They can be roughly categorised into four main activities. Firstly, the development of an airflow valve specifically designed for this purpose. Then, a market survey was conducted to select the electronics needed to set up the control circuit (hardware). Another work activity focused on developing the software architecture to implement the control strategy. A suitable mock-up was developed in parallel to test, demonstrate, and track progress in the other work packages. This section starts, however, with an outline of some fundamentals (Section 2.1). The main work packages are then presented and discussed in Section 2.2 (Control System Development).

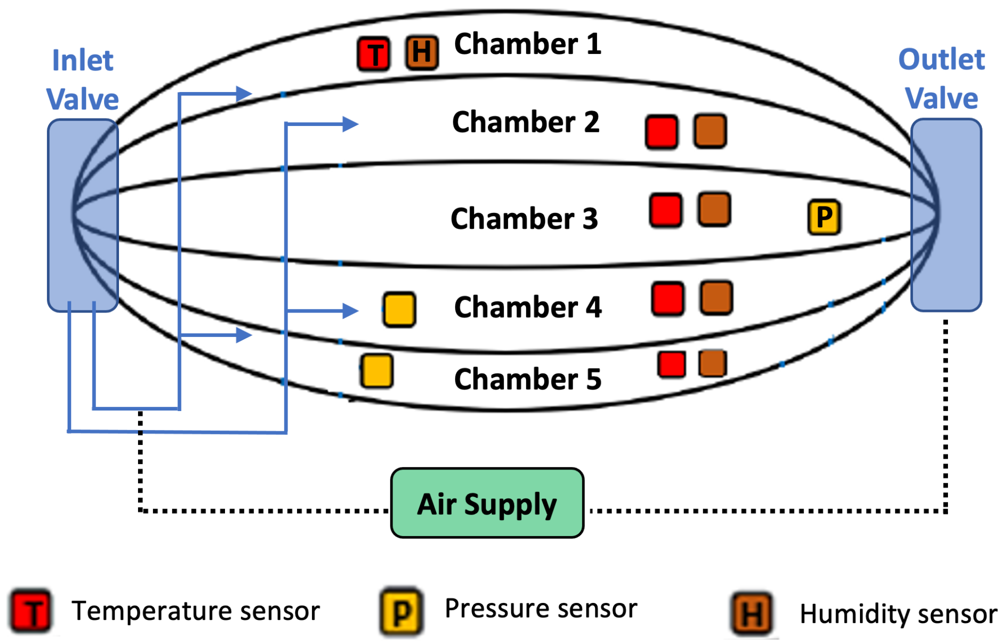


FIG. 10 A schematic of a 6-layer ETFE membrane cushion indicating the proposed valves and sensors

2.1 DEFINITION OF CONTROL SPECIFICATIONS FOR COATED (FAÇADE AND ROOF) MEMBRANE AIR CUSHIONS

Generally, to provide the control unit with the necessary input information, air temperature (T in °C), relative humidity (RH), and air pressure have to be measured by suitable sensors and then processed by the controller to achieve the desired cushion operation. Whereas temperature and pressure can be processed directly by the controller, a solution had to be developed to optimise humidity control within the cushions. During work on the control strategy, it became clear that temperature-dependent, and therefore variable, RH values were not suitable for humidity control inside the chambers to avoid negative, condensation-related effects on coating materials. As part of the project for the envisaged application, a novel approach to a dew-point-related humidity controller for conditioning the supply air of foil cushions was developed. Theory and calculation methods are described in the following section.

2.1.1 Humidity Control

Because measuring dew point is complicated, expensive, and requires a large, expensive setup of a cooling unit, a metal sensor, and condensation detection that cannot be integrated into the distributed cushion sensors, the dew point calculation approach seemed more viable. As the required input values of RH and temperature for the calculation were read by the most common combined temperature-humidity sensors, it also seemed favourable regarding costs and wiring effort.

Definitions and fundamentals:

- Air is a mixture of various gases. One of these gases is water vapour. However, the amount of water vapour that can be contained in the air is limited. The warmer the air, the more water vapour it can contain before condensation occurs.
- RH indicates the percentage of the air's maximum water vapour content it currently contains. Since the maximum water vapour content increases with rising temperature, the RH decreases with rising temperature (and vice versa).
- Dew point temperature (TD in °C) is defined as the temperature at which the current water vapour content in the air is at its maximum (100% RH). TD is therefore independent of the current temperature.

The dew point calculations in this paper are based on the approximation formula for saturated vapour pressure (SDD in hPa), known as `Magnus´ formula (s. equation 1), which allows for calculating TD from air temperature and relative humidity values (Stefan Ochs, n.d.). RH is defined as the ratio of the current vapuor pressure (DD in hPa) to the SDD (transformed equation 2). SDD is defined to be equal to the current DD at TD. These two definitions lead to equation 3, the formula for calculating RH from TD. Equation 4 describes the reverse calculation of TD from the RH and the current temperature. This latter equation is the first equation solved for temperature, in which the current vapour pressure (not the current saturation vapour pressure) is used as input, so that the dew point temperature (not the normal temperature) appears as the result.

$$SDD\,(T) = 6.1078\ \times 10^{\frac{aT}{(b+T)}} \tag{1}$$

$$DD\,(RH,T) = \frac{RH}{100}\ \times SDD(T) \tag{2}$$

$$RH\,(T,TD) = 100\ \times \frac{SDD(TD)}{SDD(T)} \tag{3}$$

$$TD\,(RH,T) = \mathrm{b}\ \times \frac{\mathrm{v}}{(\mathrm{a}-\mathrm{v})} \quad \text{where } \mathrm{v}\,(\mathrm{RH},\mathrm{T}) = \log\left(\frac{\mathrm{DD}(\mathrm{RH},\mathrm{T})}{6.1078}\right) \tag{4}$$

Parameters:

$$(\mathrm{a,b}) = \begin{cases} (7.5,\ 237.3), & \text{for T} \geq 0 \\ (7.6,\ 240.7), & \text{for T} < 0 \text{ above water (dew point)} \\ (9.5,\ 265.5), & \text{for T} < 0 \text{ above ice (frost point)} \end{cases}$$

2.1.2 Temperature and Pressure Control

The temperature and pressure sensor readings could be processed directly by the control unit without further physical or mathematical logic. The temperature sensors, often combined with an RH sensor, are readily available, inexpensive, compact, reliable and accurate, and therefore selected for the project. The same applies to the air pressure sensors. All sensors and devices used in this project are briefly discussed in Section 2.2.3.

2.2 CONTROL SYSTEM DEVELOPMENT

Developing a control system ideally necessitates a control strategy, measurements, data processing, monitoring, data evaluation and communication.

2.2.1 Control Strategy

As a basis for further work, the common, mostly uncontrolled, continuous air supply and drying operation was conceptualised into two operating modes: 1) flushing operation for condensate prevention and 2) normal operation to maintain pressure. Then, the flushing operation is distinguished between flushing with untreated /or dried outside air. This section presents the development of the control strategy for both flushing and normal operations.

List of abbreviations used in Section 2.2.1:

- Ta: Ambient Air Temperature: Temperature of the outside air surrounding the membrane cushion system
- Tf: Foil Surface Temperature: Temperature of the membrane foil surface
- Tpi. Dew Point Temperature Inside: Dew point temperature of the air inside the cushion
- Tpa: Dew Point Temperature Outside: Dew point temperature of the outside air
- TD: Dew Point Temperature: Temperature at which air becomes saturated and condensation begins
- T: Air Temperature: General air temperature (inside or outside, depending on context)
- RH: Relative Humidity: Ratio of actual water vapour pressure to saturation vapuor pressure at a given temperature
- °C Degree Celsius

Extensive parameter studies were carried out to verify and optimise the control strategy. In general, a dew-point-based control strategy was developed to define the criteria for switching the flushing mode on or off with or without drying (Section 2.1.1). It was adapted to the operating conditions (e.g. indoor and outdoor temperature and humidity ranges, as well as the psychrometric interactions of foil constructions). Conversely, normal operation for maintaining pressure should be carried out after filling the cushions, provided that flushing is neither possible nor necessary.
Flushing the cushions with ambient air is permitted and should be done whenever the TD of the outside air is lower than that of the inside air. This results in indoor air conditions with the lowest possible dew point and minimises the risk of condensation, even without operating the dryer, which leads to high energy consumption. Next, the operation of the cushions under real conditions was examined. In reality, the foil temperature can be influenced not only by slow ambient temperature changes, but also by surface temperature changes independent of the ambient air, such as hail during a thunderstorm on the outside layer, or technical measures such as air conditioning in a climatised room, or in a roof/façade cushion construction. To determine the switching points between flushing and normal operation of the controller, the inside and outside humidity (0–100% RH) and temperature (-15-45 °C) conditions were varied within the scope of validity of Magnus' formula for the parameter studies to determine the respective TDs. The calculated values were then evaluated in terms of the switching conditions between the predefined operating modes: Filling, flushing (with or without drying), and pressure maintenance (normal operation). The control criteria for the different operating modes are described below in Fig. 11.

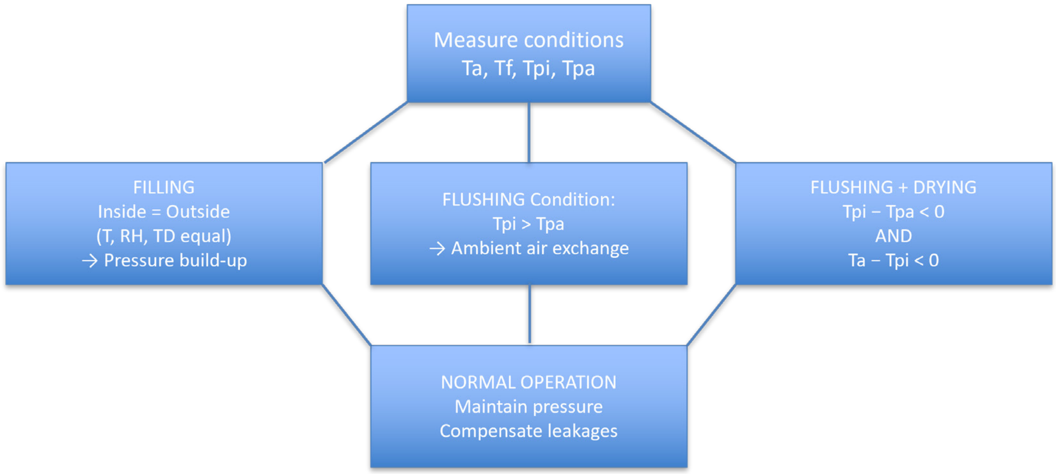


FIG. 11 Membrane cushion control strategy-operation modes and mode-switching conditions

The following operation modes and on-off criteria were defined for the parameter studies:

- **Filling**: At the time of filling, the temperature, RH, and TD of the air inside and outside the cushion are the same (in all chambers). In this case, neither flushing nor drying is necessary. Normal operation continues until the desired pressure is reached and continues compensating for any leaks if present.
- **Flushing**: The system switches to flushing mode when the dew point temperature inside (Tpi) is higher than the outside temperature (Ta), corresponding to the foil's surface temperature. Under this condition, there is no need for drying; untreated ambient air can be used directly for flushing. In all cases, air filtration is needed, however.
- **Drying**: Drying of the supply air is necessary when the Tpi falls below the dew point temperature of the outside air (Tpa) and if flushing is required at the same time (Ta < Tpi). Switch-on criterion for drying of outside air as supply air for the cushion: Tpi – Tpa negative and Ta-Tpi negative = flushing and drying on. Under those (idealised) criteria, there is no need to dry when flushing is required at the same time, as these two criteria exclude each other.
- **Operation in reality**: In practice, however, there might be cases where the foil temperature is below the outside dew point and the ambient air temperature. Tf-Tpi negative: flushing and Tpi-Tpa negative: drying on. So, there are cases in which the dryer must be operated. These are temperature influences on the foil temperature that are independent of the outside air conditions.
- **Switching off both drying and flushing**: If TD of the supply air falls below the previous measured TD of the cushion (after a complete air exchange), the criterion for drying operation (Tpi-Tpa = negative) is no longer met: The dryer is switched off. However, the flushing criterion is still met. Since the new Tpi is now based on the conditions of the previously dried supply air, the comparison to the outside air is made after the next measurement interval. This leads to the flushing process being switched off, as Ta-Tpi is no longer negative and the "flushing on" criterion is therefore no longer met. From now on, normal operation resumes, i.e. maintaining the desired pressure in the cushion.

The cases that represent the most energy-intensive operation of a membrane-cushion system (flushing + drying caused by changes in foil temperature independent of the outside temperature) can be detected with the proposed dew point control, and countermeasures can be taken by the controller. Flushing and drying are carried out as needed to meet the set goals, and drying in particular is performed only in exceptional cases.

2.2.2 Mock-Up Design

To take the experiments from previous research projects (J. Cremers et al., 2020; Jan Cremers et al., 2019; Hinze et al., 2020; Manara et al., 2018; Siefert et al., 2019) to the next level, it was agreed to adopt a full-size mock-up in this project. Moreover, a modular design was introduced in this work to allow for a more flexible operation and handling during testing. The mock-up imitates a typical membrane cushion measuring 2 m x 3 m (Figs. 12 and 13). The removable frame structure offers the flexibility to vary the number of ETFE layers of the cushion and hence the number of the resulting air chambers. The multiple (normally closed) holes around the perimeter of each frame enable direct interaction with the corresponding air chamber at any point on the frame (Fig. 14). This facilitates measurements and provides a wide range of testing conditions. The mock-up also includes a customised table that can be easily dismantled. This modular design offers a non-bulky membrane cushion structure with removable ETFE foils, and the whole mock-up can be disassembled and transported to different testing sites. Furthermore, the table was equipped with wheels to enable both indoor and outdoor testing at the same test facility.

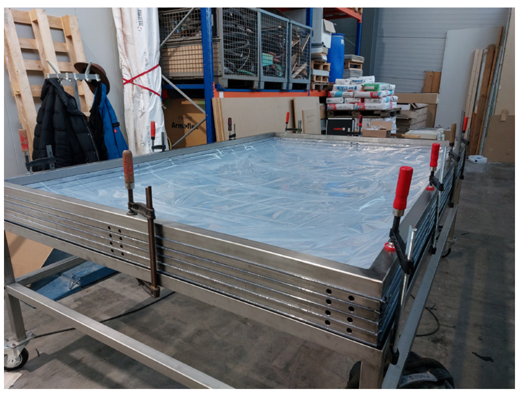


FIG. 12 The mock-up after full assembly in the lab: Air chambers are not yet connected to an air supply (deflated), and not all holes are sealed or connected yet.

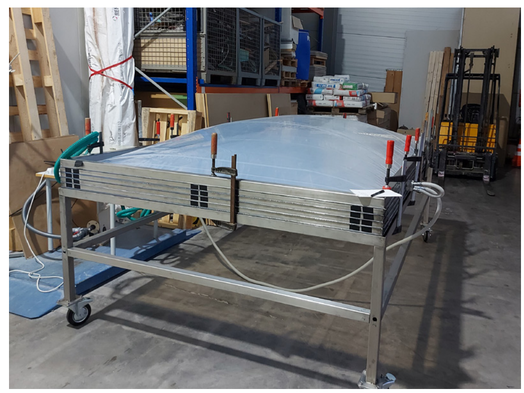


FIG. 13 The mock-up after full assembly in the lab: Air chambers are filled with air (inflated)

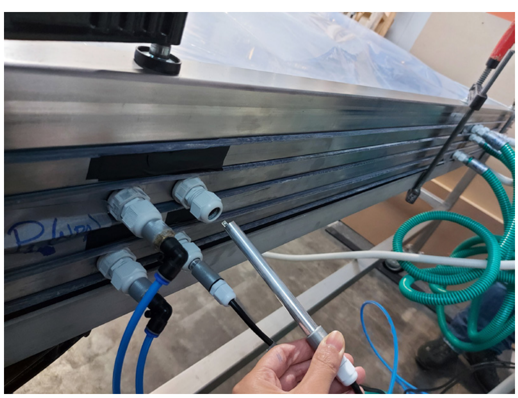


FIG. 14 Different sensors connected to the air chambers of the Mock-Up through the holes all around the frames: The blue hoses are sampling the air of each air chamber to the pressure sensors, the black cables connect the temperature sensors, and green hoses transfer the airflow between the air chambers and the air supply system

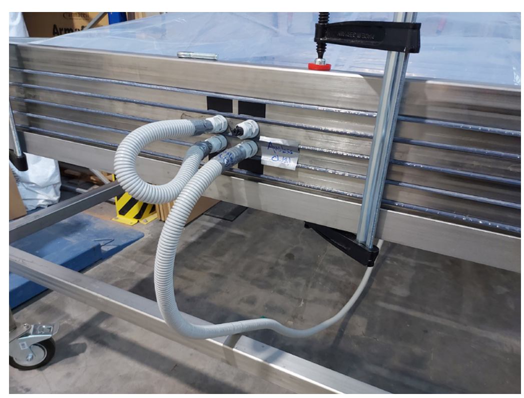


FIG. 15 Interconnecting the four air chambers of the mock-up using by-passes, forming 2 air chamber-groups

Although the mock-up of this project was designed and manufactured with 7 frames to accommodate a 6-layer membrane cushion, it was decided to configure it with only 5 ETFE foils, i.e., fixed using only 6 frames, forming a 4-air chamber membrane cushion. The two inner air chambers were interconnected via a short hose that bridges two holes in their corresponding metal frames (Fig. 15). The same procedure was applied to interconnect the two outer air chambers of the 5-layer membrane cushion mock-up. Through such a connection, two air chamber-groups were eventually formed in the mock-up: an inner one (notation: Chamber-Grp#1) and an outer one (notation: Chamber-Grp#2). Each chamber group needs a set of devices (measurement sensors, valves, and actuators), as explained in the next section.

2.2.3 Controller and Hardware Design

The low-cost, energy-efficient, and mass-produced ESP32 chip was chosen as the MCU (Micro Controller Unit) of the control circuit. Generally, in large-scale membrane cushion systems, there would be a control circuit for each air cushion. Depending on the number of air chambers formed within a membrane cushion, a range of sensors, airflow control valves, and electrical components would be identified. Fig. 16 shows the control circuit that was developed for the mock-up of this project. As can be seen, some electrical (relatively bulky) devices, e.g., some sensors and actuators, are (and will be) connected to it. Therefore, an airtight control box was considered to enclose all the hardware of the mock-up. This control box will act as a black box, interfacing the air supply system from one side (fan, dryer and later in a final system also filter) and the air chamber-groups of the mock-up from the other side (Fig. 17). When tightly locked, the air enclosed by the control box represents the conditions of the air supply.

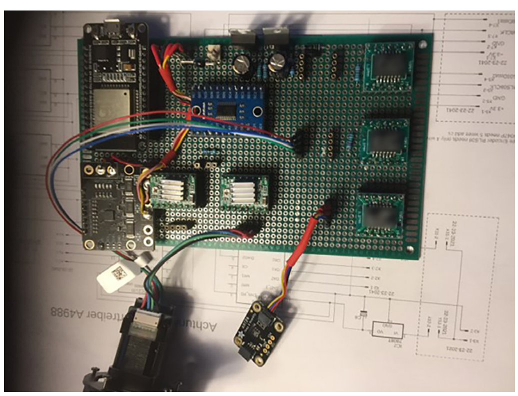


FIG. 16 The control kit developed from a circuit diagram into PCB (printed circuit board), ready to be integrated into the control box of the mock-up

FIG. 17 The control box is connected to the mock-up on the left side, and the air supply system is directly connected on the right side

For its two air chamber-groups, two sets of devices were provided for this mock-up. For example, as depicted in Fig. 18, two stepper motors with their accessories (e.g., motor drives and position sensors) are used. However, for the pressure and temperature measurements, more sensors were used depending on the different air conditions to be measured. For instance, three pressure sensors were considered–one sensor for each of the two air chamber-groups and a third one was needed to measure the pressure of the air supply (P_Fan). As for temperature (and RH) measurements, the same was applied in addition to a fourth sensor to monitor the ambient conditions.

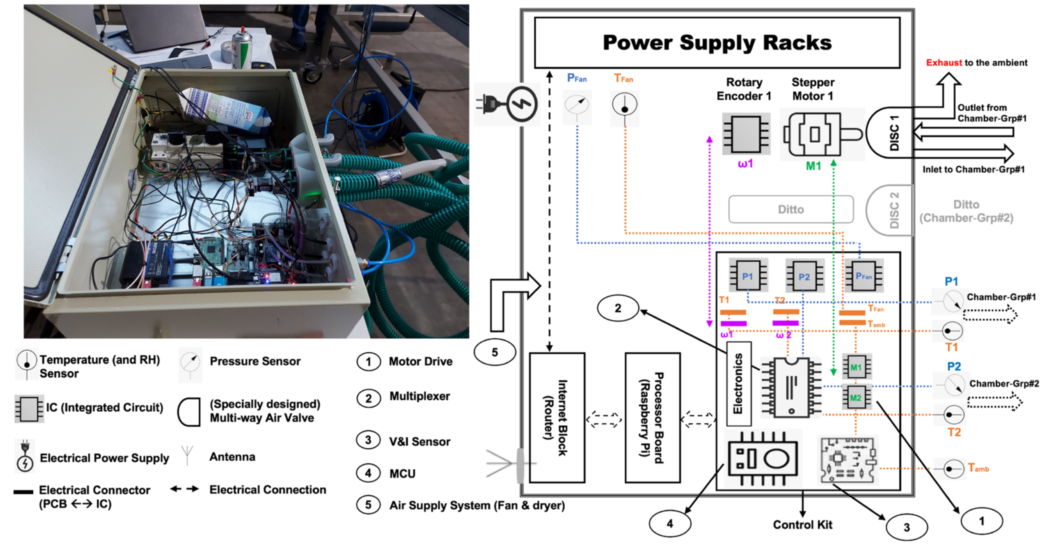


FIG. 18 Left) The control box in real installation (showing the special enclosure-interface design for the two discs to be connected to the inlets and outlets of the air chamber-groups of the Mock-Up via the green hoses) – Right) A schematic of the control box (indicating the main components and explaining the electrical connections and sensor signals)

Fig. 18 illustrates all the hardware inside the control box, which was configured to remotely operate the mock-up in this project. The control kit consists mainly of a controller (MCU), some sensors (for temperature, relative-humidity and pressure), motor-drives (to eventually actuate stepper motors), rotary encoders (angle position sensors), and electronics (e.g., communication switch(es), voltage & current sensors, protective capacitors and resistors). Each actuator (stepper motor) is mechanically coupled to an airflow valve via a shaft to transmit rotational movement. In this project, a special multi-way/multi-mode airflow control valve was designed by the project partner, which will be referred to as "disc" (Fig. 18, top-right). The main feature of this disc (airflow valve) is its dual functionality, operating in either of the two main modes: normal or flush (as explained earlier in Section 2.2.1). Those two different operation modes are physically distinguished within the physical body of the valve (disc), by assigning a specific path for the airflow with different inlets and outlets.

The real-time measurements are processed by the MCU according to the uploaded program, which corresponds to the adopted control strategy. Depending on the operation mode (normal or flush), whether in natural or forced conditions, a control signal (flag) will be generated to activate the corresponding physical part of the disc, as explained above. In a second step, and depending on the measurements (current operating conditions) and the desired set points (required action), the optimal opening size for the addressed airflow path is calculated. The latter is converted within the control program to an equivalent number of steps for the stepper motor to move in a certain direction, depending on the motor's current position, to eventually adjust the valve-opening (by opening or closing it, or even by standing still). These control signals (number of steps and rotation direction) are consistently communicated to the motor-drive, which in turn actuates the stepper motor. This control process runs in a closed loop using feedback signals from the rotary encoder, which interactively detects the current position of the stepper motor. The pressure (and later also the humidity) of the air supply system is controlled to achieve the desired conditions (Section 3.4). The aim is to fully regulate the airflow moving from the air supply unit to the air chamber (through the disc) to ultimately maintain a reliable long-term operation of the membrane cushion. It is worth mentioning that the control operations of the two motors (discs or air chamber-groups) are independent. However, the inside conditions of each air chamber-group affect the other one, of course, as they are adjacent to each other.

2.2.4 Software Architecture

The controller used in this work (ESP32) was programmed using the open-source Arduino Software (Arduino IDE: Integrated Development Environment). The adopted control strategy was written as code using the Arduino simplified C++ programming language. The resulting "***.ino" file (Sketch) was developed in stages to test each hardware component separately, with the control operation tested at the end. The complete final Sketch for the mock-up of this project was compiled and uploaded to the ESP32 MCU integrated into the control kit inside the control box. This cushion controller is autonomous and responsible for all standard operations, e.g., measurements and pressure control. On the other hand, for larger-scale systems (i.e., consisting of more than one cushion and hence more than one cushion controller), a main controller shall be used. This main controller performs various tasks, including: communication with all other cushion controllers (sending requests to / collecting data from all existing ESPs), status analysis of all cushions and discs (e.g. failure detection), visualisation of data (monitoring), internet connectivity, and data provision for facility management. Fig. 19 shows a schematic diagram of the general communication layout for such control systems, taking future expansions into account (e.g., larger membrane cushions systems), which would ideally use the CAN-Bus system.

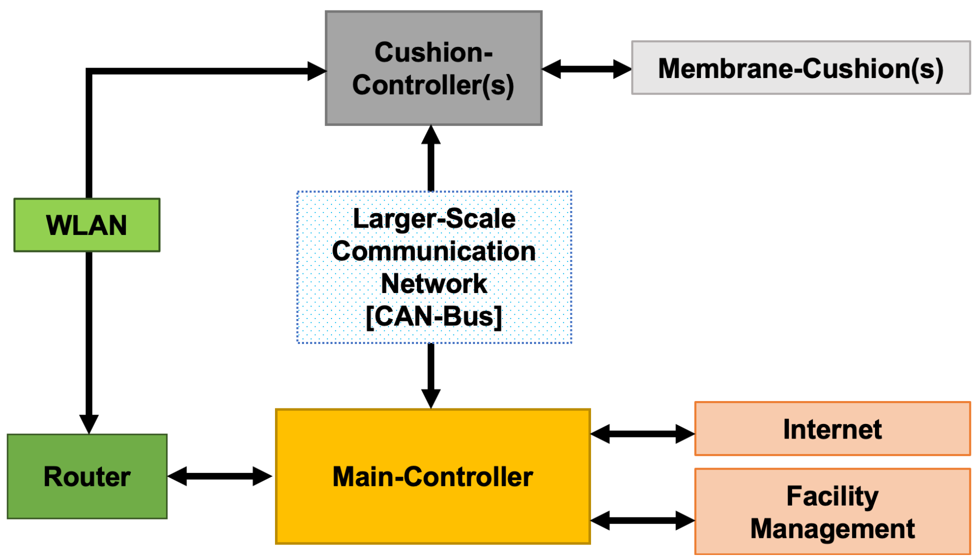


FIG. 19 A schematic of the general communication layout for the proposed control system

As indicated in the schematic in Fig. 18 (bottom left), the single-board computer Raspberry Pi (Raspi) was integrated into the control box of the mock-up as the main controller. The Wi-Fi router was connected to the Raspi to provide WLAN (Wireless Local Area Network). This was important mainly to connect the cushion controller(s) (ESP32) to the main controller (Raspi). Moreover, internet connectivity enabled all project partners to remotely access the mock-up monitoring program from different premises, as the Raspi also supports connecting to display screens via its HDMI ports. This makes it possible to visualise and monitor any control signal and/or measurement quantity of interest (see display area number (3) in Fig. 20). For that purpose, a user-defined Linux-based software had to be developed on the Raspi OS (Operating System) to introduce a GUI-Program (Graphical User Interface). That user-friendly, interactive environment was designed to accommodate real large-scale systems (up to 50 membrane cushions).

However, only one cushion-controller was activated, namely that of the mock-up, for the experiments which could be conducted within the time frame of this research project (see display area number (4) in Fig. 20). This Raspi program was also intended to store measurements and to process data for analysis and special operations for the discs. To overcome the lack of internal storage featured by the Raspi, a micro SD card was used for data logging and storage.

3 RESULTS & DISCUSSION

This section provides an overview of the experimental work that could be carried out during the project's lifetime.

3.1 COMMISSIONING AND START-UP

Due attention was paid during the assembly of the six metal frames of the mock-up to form the agreed-upon 5-layer ETFE membrane cushion. The firm fixation of each ETFE foil between the two adjacent frames ensures minimal leakage. This is normally achieved via clamping or welding. However, it was presumed that additional measures would be needed here due to the exceptional no-welding option of the ETFE layers. Therefore, to compensate for this, multiple screw-clamps were used along the mock-up perimeter to maximise the force pressing the five layers together at the edges (Figs. 12 and 13). Finally, the holes of all frames were sealed via duct tape, except for those which were decided to be used later on, whether for bridging two air chambers together or as direct connecting points for air-supply inlets and outlets, or for different sensors as needed (Figs. 14 and 15), considering providing optimal sealing via suitable cable glands.

After the setup, the control box was brought to the test facility and connected to the mock-up (Fig. 17). To ensure proper operation and reliable system results, it was crucial to retest the functionality and accuracy of each component as it was integrated into the mock-up. All sensors connected to the air chamber-groups (pressure, temperature and relative humidity) performed well (Fig. 14). Nevertheless, the disc required a few modifications during installation within the control box to better integrate with both the mock-up and the stepper motor. This was achieved by developing a suitable enclosure, along with the shaft and some mechanical fittings (Fig. 18, left).

To start up the system, all electrical and electronic connections were carefully plugged in. The software programs were also installed and run. After several debugs, the basic functionality of the system was validated. As shown in Fig. 20, all control signals and quantities of interest can be well monitored. The developed GUI offered an easy interaction with the mock-up. The frequent oscillations of the valves (the purple line on the graph), and hence the opening size of the valves and, eventually, the pressure signals (the red and green lines), indicated, however, the need for optimisation, as will be discussed in section 3.3.

FIG. 20 A screenshot of the GUI of the real-time monitoring program developed for the proposed control system

3.2 INVESTIGATIONS ON AERODYNAMICS INSIDE AIR CHAMBERS

In order to define ON-OFF conditions and duration of the flush mode, insights into mass flow-related fluid dynamics of the feed air under different flow patterns (e.g., cross flow, linear flow) and in relation to different inlet points had to be gained

Several experiments were carried out to measure pressure drops for varying feed air flow rates and to determine air distribution, flow patterns, and dead spots inside the membrane cushions, as well as the duration of flush air injection into the cushions.

Regarding mass flow, several variations were tested to optimise the relationship between the minimally necessary flush air flow, thereby reducing pressure drop (energy saving) and even flush air distribution. Furthermore, dead spots that create air-cushion spaces with no air exchange have to be avoided. In theory, the most effective complete air change can be achieved by an even front of flush air moving in a straight line through the cushion without mixing with residual air. This would require a single air change of the cushion volume to exchange the inside air by flush air. To minimise flush mode operation time and achieve a fast system reaction time, the air change would be carried out at the maximum air flow possible within the membrane cushion design pressure range (500 Pa max. design value). The experiments showed that in the given setup, the achievable mass flows for the flush feed air due to pressure drops were far below the technical specifications of the supply-air fan and reached a maximum of 9 m^3/hr (interpolated) at a required fan pressure of 500 Pa, suggesting further investigations on aero-dynamically optimised cushion in- and outlets (Fig. 21).

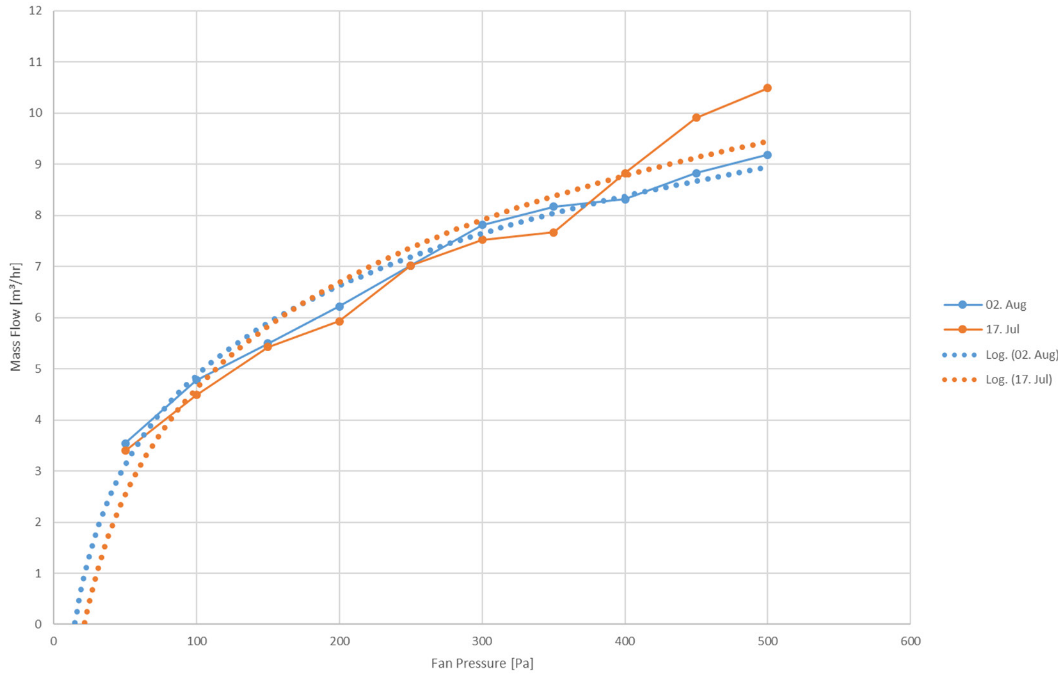


FIG. 21 Measured and interpolated mass flow rates in relation to the required fan pressure

Not only limited airflow, but also uneven feed air distribution resulting in dead spaces with low air exchange and mixing under real conditions, led to a further extension of the flushing time (Fig. 22).

3.3 OPTIMISATION MEASURES

Leakage through the frames of the mock-up was expected. Once the operation started and the air chambers were inflated with air, a basic manual inspection was performed all around the frames to locate leakage points. Modelling clay was used to improve the sealing at those spots (Fig. 23, 24).

The material from which the disc was manufactured, as well as the mechanical coupling to the stepper motor, affected the rotational dynamics and stability of that part and hence the overall system performance. All components of this specific mechanical system have been continuously enhanced.

Finally, the preliminary monitoring results (Fig. 20) showed the need for signal conditioning. That was approached by upgrading the software of the cushion controller–namely by implementing and testing different feedback control techniques, e.g. P (proportional), I (integral), D (Derivative), PI, and PID-controllers. Each has different pros and cons when adjusting the output signal as a function of the error, e.g., overshooting or slower response time might occur. Therefore, most of them were added to the ESP code to be able to test them all. The Raspi program was modified accordingly so that the user can easily choose the controller type and configure it by entering the necessary parameters as indicated on the upgraded GUI.

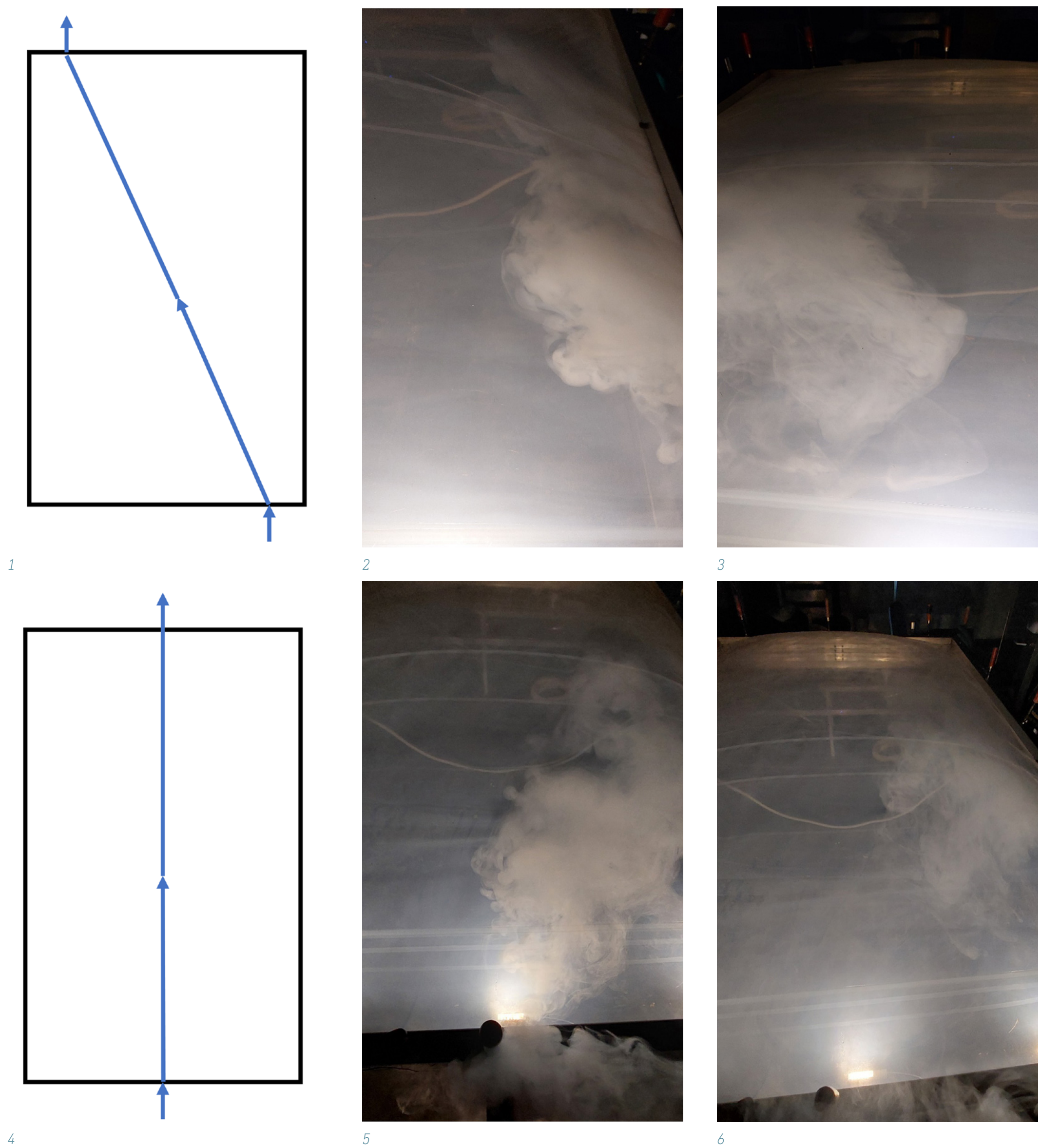


FIG. 22 Flow visualisation by tracer smoke to determine the required air exchange rate, detect dead spaces, and determine the actual flow patterns in the cushion layers for cross (top) and linear flow (bottom)

FIG. 23 Sealing improvement at distinct leakage points after the mock-up entered service

FIG. 24 Sealing improvement at distinct leakage points after the mock-up entered service

3.4 PRESSURE CONTROL IN AIR CHAMBERS

Under natural operating conditions, the previously presented control strategy should automatically run. The developed control system had to be manually tested to ensure proper operation in both normal and flush modes. The main controller (Raspi program) was coded in a pilot mode that offers a forced option (commands entered manually by the user) to switch to either of those two modes of operation. Furthermore, it allows selecting a specific air chamber (by activating the corresponding motor-drive) to test only that one if required. This convenient environment provides a broad range of testing and tracing for errors. In the (forced) normal mode of operation, the target was to check if the pressure in the air chambers is maintained at the predefined set points.

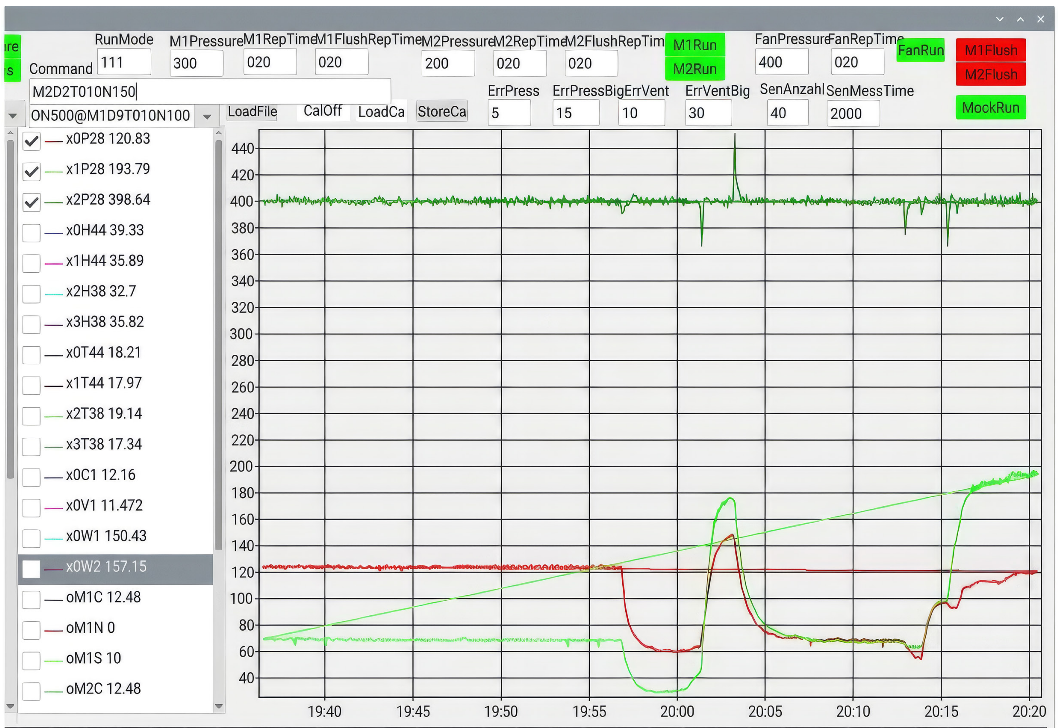


FIG. 25 A screenshot showing the pressure signals under forced and automatic control options for the normal mode of operation

It was also important to observe how the system would react to (forced) external factors and to changing the set values. This helps to expect the behaviour of the proposed control system in real operation. Fig. 25 shows the pressure signals inside the two air chambers of the mock-up. The red line indicates P1, the gauge pressure of the inner one “Chamber-Grp#1”, and the light green line is P2 of the outer “Chamber-Grp#2”, while the upper green line is the supply-fan pressure (P_Fan), which was set at 400 Pa (gauge pressure) during this part of the experiment. At the beginning, constant values of 120 Pa for P1 and ca. 70 Pa for P2 were monitored. Shortly before 20:00h, the smooth operation was interrupted by a (forced) change in P1, which was reduced to 60 Pa (user command). The immediate interaction between the two air chambers can be noticed in the falling pressure P2 at that moment to less than 30 Pa. P2 was then increased to ca. 180 Pa, which caused a surge in P_Fan as well as a following increasing pattern of P1 to ca. 145 Pa. Then the two pressures fell to ca. 70 Pa. In the final phase of this measurement, the automatic control for the normal mode of operation (according to the ESP-code) was selected (the green activated buttons at the top-middle-right). The pressure of Chamber-Grp#2 reached the preset value of 200 Pa, and P1 (while still rising) didn't reach the preset value of 300 Pa at the moment the measurement was terminated. This shows the importance of close observation of the time, heat and mass transfer related system inertias to implement appropriate response delay-times and hysteresis values to the controller software.

To closely evaluate disc performance and response, the Raspi program not only monitored the number of steps the actuators rotated, but also tested them manually. E.g., it was possible to send a user-command to a specific actuator to move certain steps in a certain direction and hence observe how the pressure signals inside the membrane-cushion respond (Fig. 20). It's noteworthy that the signals in Fig. 25 are more stabilised compared to the signals in Fig. 20. That was due to the implementation of a feedback control technique as explained in section 3.3. More experiments in real operating conditions and further investigations and analysis are still required. This is planned for the project's follow-up phase, as discussed in the following section.

4 CONCLUSION & OUTLOOK

Membrane cushion systems depend on continuous operation of an air-supply system to keep them inflated at a preset pressure while compensating for inevitable air leakage. Therefore, it is equipped with an air-dryer for dehumidification. Assuming reliable operation of such air-supply systems, failures may still occur due to external conditions, e.g. holes caused by birds. There is obviously a market need for fully automated operation–especially with the enormous progress recently made in the field of functional coatings on ETFE foils, as the pressure, humidity, temperature and stretching of the membrane cushions can lead to damage of the coating films. The research presented in this paper aimed at introducing an integrated and intelligent control system for the energy-efficient operation of ETFE membrane cushion systems without affecting aesthetics or transparency.

The experimental work is based on a single 2 m × 3 m mock-up with acknowledged leakage issues and manual sealing measures, serving as a setup for early-stage development/proof-of-concept. The control concept addresses typical project volumes, from small applications with only a few cushions to large projects with multiple roof sections and a broad range of cushion geometries. With regard to redundancies, different orientations, and façade/roof combinations (e.g., different snow and wind loads), it has to be decided whether parallel control systems are applied. For the mock-up, manual sealing efforts led to cushion tightness close to a real application cushion size tested. In a professional application, leakage is mainly an issue with regard to potential damage (vandalism, incorrectly executed maintenance, bird attacks, etc.), which can be detected and monitored by the control system developed. Cushions larger than 2 m x 3 m tend to be less sensitive to turbulences (with a better edge-to-volume ratio). Very specific geometries (e.g., with very small corner angles) would need to be investigated on a project-by-project basis through simulation or experiments.

The proposed control system relies on a novel design of an airflow valve that can switch between two modes of operation (normal and flush) depending on the actual air conditions within each air chamber. For testing purposes, a modular real-size mock-up (3 m x 2 m) of an ETFE membrane cushion was set up in an indoor test facility in Stuttgart, Germany. The mock-up is movable (to allow for future outdoor testing) and can be configured to test a membrane cushion up to 6 layers thick. In this work, a 5-layer (4 air chamber) ETFE membrane cushion was considered. However, it was configured in this project to have only two air chamber-groups. The ESP32-based control circuit, along with all other electrical and communication devices, was enclosed in an airtight control box, which included two valves to interface the air-supply system with the two air chamber-groups.

The control strategy evaluates all sensor measurements (pressure, temperature, and RH) and provides feedback to the air supply fan and the dryer to control the airflow into and out of the air chambers of the mock-up. This allows flushing the air only when needed with dry air, thus reducing fan and dryer operation times and power, and hence energy consumption.

The control system offers a user-friendly monitoring environment for remote supervision (and forced control, if necessary). The Raspi-based demonstration system was designed to accommodate experimental expansions (prototypes of 2 clusters with 4 cushions each) as well as real projects (with many more membrane cushions). First results showed that the flush mode duration significantly depends on fan power, cushion design and volume, as well as on the aerodynamic design of the air channels and the in- and outlets of the supply air. In the given setup, it was observed that the required air volume for complete flushing of the cushion was three times the cushion volume, extending the flushing time from the theoretical one to three, which is still better than the usual continuous operation. However, further airflow optimisation of the air channels inside the multi-functional valves should be achieved to minimise energy-consuming pressure drops.

To optimise the flushing process of the cushions, further investigations into air distribution and collection devices (e.g., low-velocity inlet and outlet diffusers and collectors) within the cushions should be conducted. As the data from our experiments are limited, this also applies to the quantification of achievable energy savings in a project-specific environment (for example, depending on a specific location), flush volume optimisation (for example, depending on a specific cushion geometry and the specific project environment), and other project-specific optimisations.

The monitoring results introduce the proposed system as a potential business case regarding the service of membrane cushion projects. The displayed and recorded sensor data offer new alternatives instead of the demanding "on visual basis" maintenance. To achieve market readiness of the control system, further research should be carried out on long-term testing and monitoring under real weather conditions (outdoors) of the entire setup for experimental validation of the energy consumption values expected from this work. These experiments could be accompanied by the development of a dynamic simulation model to predict the system's behaviour and efficiency. A validated dynamic simulation platform would further ease system configuration and adaptability to other cushion geometries during the planning phase of a cushion project (Borkowski et al., 2022) and during transfer to further multilayer applications such as closed cavity façades, where the same problems (e.g., condensation prevention, energy efficiency) must be solved. The large box for housing all technical components was used to test them and replace them if necessary, etc. With a view to further optimisation, the miniaturisation of the entire technology, including the valves for controlling a cushion (ready for installation in the foil cushion), was tested to the size of a cylinder (D=100 mm x 100 mm, plus air connection nozzle 25*40 or 50 x 40 mm). From the software perspective, further research could focus on error detection and the optimisation of communication protocols for CAN-Bus data transfer between multi-cushion systems, the air supply unit, the main controller, and sub-units. Furthermore, the integration of external weather forecast data would enhance reliability, provide redundancy in case of sensor error, and enable predictive control of the system.

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References

Architen Landrell. (n.d.). *Architen Landrell*. A Leading Specialist in Structural Membrane Design. https://www.architen.com/materials/etfe-foil/

Borkowski, E., Loonen, R., Trčka, M., & Hensen, J. (2022). Adaptive building envelope simulation in current design practice. Journal of Façade Design and Engineering, 10(1), 1–16. https://doi.org/10.7480/jfde.2022.1

Cremers, J., Liebhart, H., & Mirbach, D. (2020). Potential energy saving via dynamic shading with electrochromic elements in ETFE windows. *BauSIM2020*, 359–367. https://doi.org/10.3217/978-3-85125-786-1

Cremers, Jan, Mirbach, D., Liebhart, H., Marx, H., & Hajek, O. (2019). The ideal ETFE fenestration: The influence of material properties on the thermal performance. *Proceedings of IASS Annual Symposium - Structural Membranes 2019 Form and Force*, 1933–1944.

Hinze, S., Steiner, C., Fahland, M., Fahlteich, J., Schott, M., & Posset, U. (2020). *Erforschung von Rolle-zu-Rolle Technologien zur Herstellung flexibler und gebogener Fassaden- und Dachelemente mit schaltbarem Gesamtenergiedurchlassgrad : technischer Abschlussbericht für das ENOB Verbundvorhaben FLEX-G : Laufzeit : 01.06.2017-30.11.2020* (p. 109). Report (Deutsch), Förderkennzeichen BMWi 03ET1470. https://doi.org/https://doi.org/10.2314/KXP:1801353220

Knippers, J., Cremers, J., Gabler, M., & Lienhard, J. (2011). *Construction Manual for Polymers + Membranes: Materials, Semi-finished Products, Form Finding, Design*. Birkhäuser. https://doi.org/10.11129/detail.9783034614702

Manara, J., Arduini, M., Kehl, A., Siemens, P. M., Renz, J., Renz, T., Kiesel, M., Funk, M., Zabel, H., Cremers, J., Beck, A., Marx, H., & Frank, O. (2018). *Funktionalisierte Membrankonstruktionen zur energetischen Sanierung von Gebäuden (FMESG): Schlussbericht des BMWi-geförderten Projekts : Laufzeit des Vorhabens: 01.10.2015 - 30.09.2018* (p. 219). Report (Deutsch), Förderkennzeichen BMWi 03ET1309. https://doi.org/10.2314/KXP:1670860949

Siefert, W., Kinde-Hasse, B., Hildebrandt, C., Pfannkuchen, N., Zabel, H., & Cremers, J. (2019). *FOLLOW-E2 - Energiesparende funktionelle Beschichtungen von Polymermaterialien für die Folienarchitektur : Schlussbericht : Berichtszeitraum: 1.3.2017 bis 30.11.2019* (p. 125). Report (Deutsch), Förderkennzeichen BMWi 03ET1468A-E, Verbundnummer 01175546. https://doi.org/https://doi.org/10.2314/KXP:1744003343

Stefan Ochs. (n.d.). *Luftfeuchtigkeit*. https://www.wetterochs.de/wetter/feuchte.html